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Controlled Velocity Testing of an 8-kW Wind Turbine

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CONTROLLED VELOCITY TESTING OF AN 8-KW WIND TURBINE

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ABSTRACT

This paper describes a case study of the controlled-velocity test of an 8-kW wind turbine. The turbine was developed in response to the U.S. Department of Energy's small wind turbine program. As background, the prototype development is discussed. The turbine mechanical and electrical components are described. The turbine was tested on a flatbed truck and driven down an airfield runway at constant relative wind speed. Horizontal furling was used to control over-speed. Various parameters were changed to determine their effects on furling. The testing showed that the machine had insufficient rotor offset for adequate furling. Also, a rotor resonance problem was discovered and remedied. Problems associated with taking the measurements made it difficult to determine if the truck test was a suitable method for code validation. However, qualitative observations gleaned from the testing justified the effort.

INTRODUCTION

The benefit of prototype testing in product development is well known. Equally important is the verification of analytical tools used in the design development. Both processes require a test program where critical variables can be controlled and system behavior can be observed with sufficient accuracy.

This paper contains a case study of a prototype test of an 8-kW wind turbine developed by the WindLite Corporation with funding and test engineering assistance from the National Renewable Energy Laboratory (NREL). The turbine was developed in response to the U.S. Department of Energy's (DOE) Small Wind Turbine Program. The turbine was tested while mounted on a flatbed truck and driven at constant velocity along an airfield runway. The test immediately showed that the turbine geometry would not allow proper rotor speed regulation. A rotor resonance problem was also identified. In addition, data obtained from the test were invalid due to oversights in the measurement setup. These oversights will be discussed and proper remedies will be described in this paper.

Small Turbine Program

The DOE has recognized an increasing worldwide market for small wind turbine applications. To stimulate the application of advanced technology in the small turbine industry in the United States, the DOE established the Small Wind Turbine Program (Forsyth, 1997). This program was designed to serve markets in the 5 to 40-kW turbine range.

WindLite Corporation of Mountain View, California won a contract in the Small Wind Turbine Program to develop an 8-kW machine for battery-charging applications. The prototype turbine was based upon the Sencenbaugh Model 1000, which was sold in the 1970s and 1980s and tested at Rocky Flats (Higashi, 1980). A primary features of the Sencenbaugh 1000 was the use of horizontal furling for overspeed control (Sencenbaugh, 1982).

Horizontal Furling

Furling is a passive control scheme that has been used for more than a century for limiting rotor overspeeds. Overspeed control is provided by using the increasing pressure of the propeller disk area to swing the offset generator assembly with coupled rotor out of the oncoming wind flow (Figure 1). The generator offset is a key design parameter. Another geometrical feature is the tail assembly designed with its pivot axis several degrees off vertical. This slight angle allows gravity to re-open the tail after partial or full furl.

Even with a long history of field experience of furling machines, the industry's analytical basis for furling had been practically non-existent in the open literature. The DOE has been committed to improving analysis and design tools for the wind energy industry. NREL program managers expected results from the WindLite tests to be used to advance furling analytical models. Critical areas for research were center of thrust location under yawed conditions and tail vane aerodynamics.

Truck Test Background

During the initial design stage of the Sencenbaugh 1000, a full-scale model was constructed with a variable geometry chassis. The machine was mounted upon a stub tower installed in the bed of a truck. Driven at constant measured wind speeds, measurements were recorded as changes in rotor-offset distance, and tail pivot angle was modified. By careful observation of the rotor revolutions per minute (rpm), the best combination of settings was integrated to create a machine capable of maintaining safe propeller rpm under all conditions. Subtle substitutions in tail boom mass and fin weight combined with tail pivot angle resulted in a controlled and reliable system. No-load propeller rpm and controlled tail-boom movement were two critical design areas.

During development of the WindLite 8-kW turbine, several rudimentary computer simulations were under investigation, but had generated little confidence. A fundamental problem was that reliable field data of sufficient quality had been unavailable for a proper code foundation. The project team decided that a truck test similar to the Sencenbaugh 1000 effort be performed on the WindLite pre-prototype, with an increased instrumentation suite to assist with model validation.

Truck testing, more appropriately termed controlled-velocity testing, is dynamically equivalent to wind tunnel or atmospheric testing. The turbine is moved through the fluid, as opposed to the fluid moving around the turbine. Turbulence, however, is not simulated in controlled-velocity testing. Similar types of controlled-velocity testing of wind turbines mounted on truck beds are described in Bryant and Niu (1982) and Schoeberl, Kniehl, Wurz and Blaser (1987). The turbine tested by Schoeberl was of similar scale to the WindLite turbine, but was held at zero yaw error. A rail car arrangement had been used by DOE in the late 1970s and early 1980s (Balcerak, 1980) with turbines of 1-kW capacity.

We made arrangements for the WindLite truck test program to be conducted at Moffett Federal Airfield with the assistance of the NASA Ames Research Facility located in Mountain View, California. The airfield has two parallel runways of 2,804 m (9,200 ft) and 2,486 m (8,100 ft). The low traffic volume and mild winds made this site ideal for controlled-velocity testing. The airfield was also near the WindLite offices.

Truck Aerodynamic Tests

During initial planning of the truck tests, questions were raised as to the flow quality in the region of the rotor behind the truck cab. Therefore, a measurement array was constructed to determine the flow at the rotor under yawed conditions. These measurements were made one year before running the truck test with the turbine installed (Larwood, Acker and Sencenbaugh, 1998). The measurements showed less than 2% flow variation over the rotor disc for all conditions, the exception being the lower sector just aft of the truck cab. The velocity deficit at this point was larger than 50% and was highly turbulent.

We were uncertain about the effect that the cab disturbance would have on the turbine behavior. However, we were limited to where the rotor could be placed relative to the truck cab. We decided to continue with the truck test with knowledge of the flow disturbance.

DESCRIPTION OF THE TEST BED

Truck Test Tower System

The truck test tower system was designed to fit upon a 6.09 m (20-ft) flat bed truck with a vehicle weight of 9,988 kg (22,000 lb) and a bed width of 2.43 m (8 ft). The system was mounted to the bed frame at six points with bolts. The frame was also secured directly to the truck frame with two chain tie-downs.

The tower system frame (Figure 3) was a structural welded unit made of square steel tubing. The frame was designed to hold the tower section vertically with the generator installed. The tower was transported to the test site in a horizontal position and pivoted on a base system resting on a pivot bar. Erection of the tower was facilitated through the use of a portable gin-pole system and built-in winch. Although the tower erection system had been designed to lift the combined weight of the generator and tower mast from a horizontal position, an overhead crane was used to lift the generator assembly onto the tower top.

The tower was instrumented to obtain data on the turbine loads, primarily thrust. Two sets of weldable strain gages were mounted to the tower section to measure bending on two axes: longitudinal (long axis of truck) and lateral. With two measurement heights, and assuming a linear bending moment distribution, the tower top bending moment could be resolved from the tower top force. The gages were wired in a wheatstone bending bridge arrangement with four active arms. The gages were coated with the gage manufacturer's base coating and then with a co-polymer rubber-based sealant. This gage installation survived outside exposure in a California El Niño winter.

A welded structural steel frame above the top of the truck cab supported a scatter shield of 6-mm thick steel, combined with 3/4" plywood. This shield was designed to protect the truck cab occupants in the event of a blade element failure.

A mast with an upper crossbeam holding a calibrated anemometer and wind direction vane was mounted to the front of the truck. The position of the instruments was at one rotor radius upwind of the turbine at hub height. The mast was braced to reduce vibrations with guy wires to the scatter shield. An adjustable mounting pad was provided on the mast for installation of a video camera to record machine behavior during runway testing.

Concerns regarding truck-overturning moment were raised due to the relatively large turbine thrust moment arm and short truck tread width. An analysis showed that the safety factor on overturning was at 1.9, with worst-case thrust and yaw conditions. A structure was then added to the tower system to hold water bladders as ballast, thus raising the safety factor above 3.0.

Variable Geometry Test Fixture

This was the primary structure that allowed us to vary the generator offset distance and tail pivot axis angle to determine their effects on furling. These critical parameters affect the wind speed where furling is initiated, the power curve, and the loads on the turbine. The optimum geometry cannot be determined with current models due to uncertainties in the aerodynamics.

The variable geometry test fixture held the rotor, generator, and tail fin assemblies on the tower through a yaw bearing assembly. Leveling screws at the tower connection allowed for the yaw axis of the fixture to be aligned with vertical, independent of the tower alignment. Figure 4 shows the test fixture mounted on the tower without the rotor installed.

The generator was installed on a sliding arrangement that allowed lateral adjustment of the rotor shaft to yaw axis distance from 10.2 cm to 15.2 cm. This range was determined using the current analytical models of the turbine and by scaling-up of the Sencenbaugh 1000 dimensions. The offset adjustment was simply performed by loosening bolts and turning a jackscrew.

The tail boom and fin were clamped to an assembly that allowed adjustment of the tail pivot axis up to 15º off vertical. Adjustments were made with a turnbuckle arrangement. Damping in the tail pivot axis was provided with a rotary damper that was similar to a door damper. The damping force was adjustable and acted primarily in the tail opening (towards unfurl) direction. The tail could be manually furled with a cable attached to a winch on the truck bed. We manually furled the tail for making turbine mechanical adjustments and for driving the truck to and from the hangar. This safety feature should be a requirement for any furling turbine testing.

Turbine yaw and tail boom angles were measured with rotary potentiometers. Rotary motion was transferred to the potentiometer shaft through a metal drive wheel with an O-ring around its circumference. The drive wheel was held against the moving surface through the action of a torsion spring incorporated into a hinge design.

Turbine Rotor

Philippe Giguere and Michael Selig of the University of Illinois at Urbana-Champaign designed the blade planform. Although the latest in rotor optimization techniques was used to design the turbine rotor, the primary driver was the need for simplicity of construction. The planform incorporated SG6050/6051 airfoil profiles modified for the requirements of wood construction manufacturing and slight changes in airfoil contour caused by normal wear. Table 1 below lists the rotor characteristics.

Table 1. WindLite Rotor Characteristics

Item	Description
Rotor Diameter	6.7 meters
Number of Blades	3
Configuration	Upwind
Rated speed	10.5 m/s
Rated power	8 kW
RPM at rated	220 kW
Rated Tip Speed Ratio (TSR)	7.0
Airfoils	SG6050/6051 modified
Root/Tip Chord	23 / 11.5 cm, non-linear taper
Twist	Approx. 6°, non-linear
Base Material	Laminated Sitka Spruce
Coating	Ceconite Fabric/Epoxy
Blade Weight	9.5 kg

The rotor was fastened to the generator shaft with a series of compression plates (Figure 5).

ELECTRICAL SYSTEM

The WindLite turbine was to be designed for battery charging in village power applications. The generator control design utilized peak power coefficient (C_P) tracking that was developed at NREL for small turbine applications (Muljadi, Butterfield and Migliore, 1996; De Broe, Drouillhet and Gevorgian, 1999).

System Configuration

Power output of the generator was rectified by a three-phase diode bridge and fed to the 48-V DC battery bank (Figure 6). The generator delivered rated power into a 48-V DC battery bank at 230 rpm. Excess power was diverted into a 10-kW resistive load bank, to avoid overcharging the batteries during the truck test. The load bank could be controlled in 150-W increments from the cab of the truck during the testing procedures.

Peak Power Tracking Field Converter

A portion of the generator output power was tapped from the rectifier output and circulated back into the generator field winding via sliprings to provide machine excitation. The peak C_P-tracking controller was responsible for regulating field current, such that the turbine was maintained at peak aerodynamic efficiency over the operating speed range.

The block diagram of Figure 7 provides an overview of controller architecture. An outer peak-power tracking loop acted to enforce generator operation along a specified power vs. rpm curve. This outer power control loop produced a field current reference signal (IF*) for the inner current feedback loop. The inner loop then forced the actual field current (IF) to equal commanded field current. The power electronics was the “actuator” of the inner current loop that sourced current to the field winding. This circuitry was a pulse width modulation (PWM) switching converter that was designed to handle approximately 1.2 kW at rated machine excitation. Generator output power was thus controlled by the outer loop via modulation of field current.

Machine rpm was monitored by feeding stator voltage through frequency/voltage conversion circuitry. The resulting rpm signal was input to two piecewise-linear networks that produce feedback and feed-forward terms; the feedback term was used as the power reference signal (PDC*) in the peak-power loop. The feed-forward term was included to allow a reduction in feedback gain, enhancing closed-loop stability margins.

Several limit and regulation set points were included to keep the system within safe electrical operating boundaries. Activation of the limit circuitry reduced the intermediate field current command (IF*), overriding peak-power tracking operation. Both the field and battery charging currents were electronically limited to maximum set-point values. Additionally, battery voltage was regulated by this same mechanism.

A scatter plot of TSR versus rotor speed (Figure 8) for several concatenated data sets indicated that the controller was loading the rotor as designed, maintaining the optimal TSR of about 7.5 over much of the range. The TSR in the cut-in region was intended to be about 10, to avoid loading down the rotor when it was first developing lift.

DATA ACQUISITION

All measurements were recorded using a Campbell Scientific 21X datalogger on loan from NREL. Table 2 shows the list of measurements. The datalogger was set to sample at 5 Hz, the maximum rate with our channel setup. The datalogger was controlled from the truck cab with a laptop. Usually 2-minute runs (approximate memory capacity of 21X) were taken and the files were immediately downloaded from the datalogger to the laptop.

A custom sensor interface circuit board was designed to provide signal conditioning between the raw sensor outputs and the data logger. This circuitry provided for differential sensing, filtering, scaling, and calibration of the individual channels. This board also provided outputs for indicators in the truck cab.

Table 2. Truck Test Measurements

Measurement	Device	Truck Cab Indication
Tower Bending Moments (4 total)	4-active arm strain gage bridge	none
Tail Angle	potentiometer	dial indicator
Yaw Angle	potentiometer	dial indicator
Windspeed	AC output cup anemometer	digital readout
Wind Direction	wind vane potentiometer	none
Generator RPM	frequency to voltage converter	digital readout
Battery Voltage	voltage divider	digital voltmeter
Battery Current	resistive current shunt	digital voltmeter
Generator Power	current × power	digital voltmeter
Field Current	hall effect sensor	digital readout

TEST MATRIX

The test matrix allowed a progressive approach to testing by limiting system stress to low levels at the beginning and then slowly approaching the ideal crossover. The testing began with the rotor-offset distance at maximum and tail pivot angle at minimum. This was intended to create a condition of early furling to reduce system loads.

The test was to begin with a rotor offset distance of 15.2 cm and tail pivot angle of 5º. Runs at 2.2, 4.5, 6.7, 9.0, 11.0, and 13.4 m/s were to be performed in no-wind conditions. At the end of the series run, the tail angle was to be changed to the next larger angle.

During each run series, the individual runs were to be broken down into one run under no load conditions, and another run was to be performed under full load conditions.

RESULTS AND DISCUSSION

Initially, a series of test runs beginning at the test matrix point of maximum offset (15.2 cm) and minimum tail inclination angle (5º) were performed on the runway through speed ranges of 2.2 cm to 11.0 m/s, in 2.2 m/s increments. A series of five runs at each wind speed with duration of 2 minutes were performed. During this period no furling action was seen. However, power, rpm, and TSR appeared to track as predicted.

Inadequate Furling

From the beginning of the tests, it was apparent that the turbine rpm was not being regulated under load with the generator offset at the maximum position (15.2 cm) and with the tail pivot at a minimal stable position (3°). Lower tail pivot angles resulted in erratic tail behavior.

The tail boom assembly was then made as light as possible to assist in furling, but there were concerns about the turbine center of gravity (CG) moving too far forward. A weight pan assembly was then added aft of the yaw axis (Figure 5). Initially, the influence of the weights was most evident with the addition of a maximum of two (out of four) weights, the most apparent observation being a drop in loaded rotor rpm with corresponding furling enhancement. As the test progressed with lower mass fin assemblies and shallow tail pivot angles, the benefit of additional weights was not observed.

Runs were also performed at offsets of 12.7 cm and 10.2 cm, which showed progressively less furling as expected. In the case of the 10.2-cm offset, minimal furling was observed and the no-load rotor rpm quickly exceeded the imposed limit of 300 rpm.

A re-design of the variable geometry sliding plate was undertaken and fabrication completed. This modification allowed the rotor offset to progress through a range of 20 cm to 35.5 cm measured from the center of machine yaw to rotor centerline. The test campaign ended before increased offset could be incorporated into the test fixture.

Electrical Control Problems

Field excitation was limited to approximately 32 amps by the electronics and was not field adjustable; this limitation caused the loaded rotor to become progressively, or at times suddenly, unloaded at the higher wind speeds. This condition complicated the testing by allowing the rotor to exceed 300 rpm. With adequate furling, this condition may have not been encountered; however, runs in the 11 to 14 m/s region were limited due to this condition. If re-testing was to be done, this excitation power limit should be raised to allow the generator to produce higher outputs and more load on the rotor in this wind speed region.

Rotor Vibration Problems

When the turbine was tested unloaded at the lowest wind speed, the rotor would quickly attain a speed of approximately 320 rpm. The rotor would then buffet and quickly drop in speed, as can be seen in the time trace (Figure 9). Under consultation with NREL and other industry consultants, a recommendation was made to identify and perhaps solve a flapwise condition. The rotor was modified by the addition of a small mass in the tip of the blade to change the mass distribution and thus the frequency. An additional recommendation to delay the onset of stall was to round the square-tapered tip planform up to 1/4-chord radius.

After the rotor modification, the turbine was again tested in unloaded conditions. The truck was driven slowly to attain a rotor speed of 300 rpm. The rotor speed was progressively increased through the 320-rpm resonance point without incident. Subsequent re-testing above this point produced a resonance of about 375 rpm. However, further work will have to be done to remove any tendency for resonance.

Wind Speed and Direction Measurement Problems

Maintaining wind speed was difficult during the truck runs. Figure 10 shows a compilation of data from several runs for one turbine geometry. The three distinct swarms of data correspond to three nominal wind speeds. Note the very large variation in wind speed and turbine rpm. At the two lowest test speeds, the wind speed fluctuates ±1 m/s with the turbine speed varying ±20 rpm. At the maximum test speed the turbine speed varies ±40 rpm. Wind direction was also observed to fluctuate rapidly during the truck runs. Figure 11 shows an example time series. The wind direction varies ±5º for this segment. Though we did not think of it at the time of testing, these measurements were under the influence of the turbine.

Large errors potentially exist in the measurement of wind speed and direction. These sensors were placed one radius upstream of the turbine at hub height. Models by Anderson (1983) and Paulsen (1990) showed a potential slowdown of 10% to 12.5% in the velocity at one radius upstream due to the presence of a rotor at peak C_P. Anderson's field measurements showed a 2% slowdown at 3 radii upstream. Paulsen showed data at 0.68 diameters with a 7.5% slowdown at peak C_P. The influence is conceivably dependent on rotor thrust and yaw. Our error was that we placed the wind measurements so that they were strongly influenced by the turbine condition. This makes the wind speed and direction data invalid and irretrievable. Unfortunately, all the wind turbine data that we were interested in has wind speed as an independent variable.

The International Electrotechnical Commission guidelines for power performance measurement require anemometer placement from 2 to 4 rotor diameters upstream with 2.5 diameters recommended (IEC, 1998). A scheme to place the anemometer at a sufficient distance upstream can be found in Schoeberl, Kniehl, Wurz and Blaser (1987). Schoeberl placed the anemometer and wind vane on a separate cart at 2.5 diameters upstream of the rotor.

Tower Loads Measurement Problems

The tower loads data were shown to be of inadequate frequency bandwidth. Figure 12 shows a time history of the lower moment in the lateral tower axis with the signal amplitude peaks at one half the sampling frequency. We expected to digitally smooth the data during the reduction process. However, these data were invalid and irretrievable due to evidence of aliasing. Figure 13 shows a Fast Fourier Transform of the time series. Strong peaks at frequencies near one-half the sampling rate is indication of aliasing (Lyons, 1997). The cause of the aliasing was not determined; however, a dummy channel with a precision resistor possibly could have indicated electrical noise.

Also, the sampling rate of 5 Hz was insufficient for this application. Work by the Center for Renewable Energy Sources in Greece on small wind turbine loads monitoring showed tower loads spectral content up to the blade passage frequency (Zorlos, Theofilogiannakos and Binopoulos, 1996). For the WindLite tower loads this would indicate a required data bandwidth of approximately 15 Hz.

The tower loads data would also be invalid due to the data acquisition process. The tower moments were to be used to calculate forces and moments at the rotor. Therefore, simultaneous sampling would have been required for the data acquisition to eliminate skew errors in the time series. The datalogger we were using was not designed for this type of application.

This gage installation is also susceptible to temperature drift, which could have been determined with a dummy strain gage installation.

Turbine Yaw and Furl Measurement Problems

We also noticed that the turbine yaw and tail angle measurements were drifting by several degrees during the test runs. We suspected that the drift was initiated by the action of the yaw restraint. We speculated that at the end of a run when the machine would come up against the restraint, the resulting force would dislodge the potentiometer drive wheels. We therefore realigned the sensor zero before each run. Also the initial heavy potentiometers were replaced with smaller, lower mass units, and an over-center extension spring was used to provide more positive traction. These modifications seemed to reduce the error considerably. However we cannot be certain that there was no drift during the test run. We recommend that the O-ring drive wheel system not be used for this application and that a positive drive method such as a miniature timing belt drive or gear system be utilized.

CONCLUSIONS

Driving down an airfield runway with a 6.7-m wind turbine on our backs gave us valuable testing experience, besides providing comic relief for the control tower personnel.* We learned that the turbine test geometry had inadequate generator offset for proper furling and overspeed control. A rotor resonance problem was also identified and remedied; however, this problem would have to be addressed in future designs.

We made several mistakes in the design of our instrumentation system, thus making the data mostly invalid for analytical model correlation. Little time is available for fixing measurement system design problems (in contrast to troubleshooting) while under the momentum of field-testing. The common attitude is to press on and fix the problems in the data reduction process. We are all susceptible to these temptations, so we must be most diligent in the planning process before the test commences.

Many of the measurement problems could have been remedied by following the experience of those in the wind energy community. Primarily, we needed to place our windspeed measurements further upstream of the rotor, and we needed a data acquisition with a higher sampling rate for the tower load measurements. A general and proper approach would be to determine the required data bandwidth from experience for each measurement and ensure proper filtering and sampling to guarantee valid data within that bandwidth.

It is difficult to ascertain if truck-test data can be used for analytical model verification given the poor results of this test. Truck suspension dynamics might have contaminated the tower load data, even if we had a faster data acquisition system. Also, turbine behavior might have been seriously affected by the truck suspension and cab aerodynamics. It was difficult to maintain truck speed, and maximum speed was limited to 15 m/s. It would be worthwhile in the initial test planning stages that full-scale wind-tunnel testing be investigated, such as at the NASA Ames National Full-Scale Aerodynamics Complex.

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- Al Eggers and Ken Chaney of RANN, Inc.
- Bill Sorich, metal fabricator of the test hardware.

* One arriving pilot commented that he had spotted a low flying windmill in the vicinity. Subsequently the tower controllers proudly changed our radio call sign from NASA-1 to Flying Truck.

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FIGURES

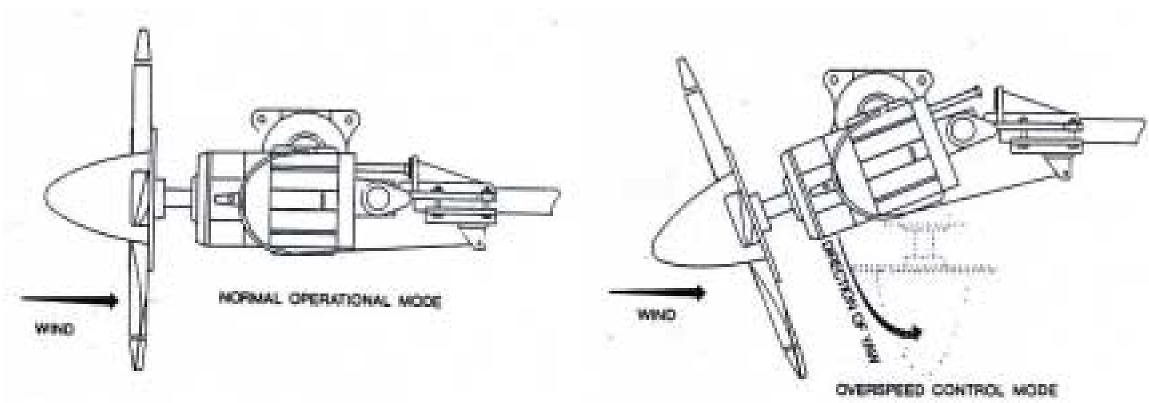
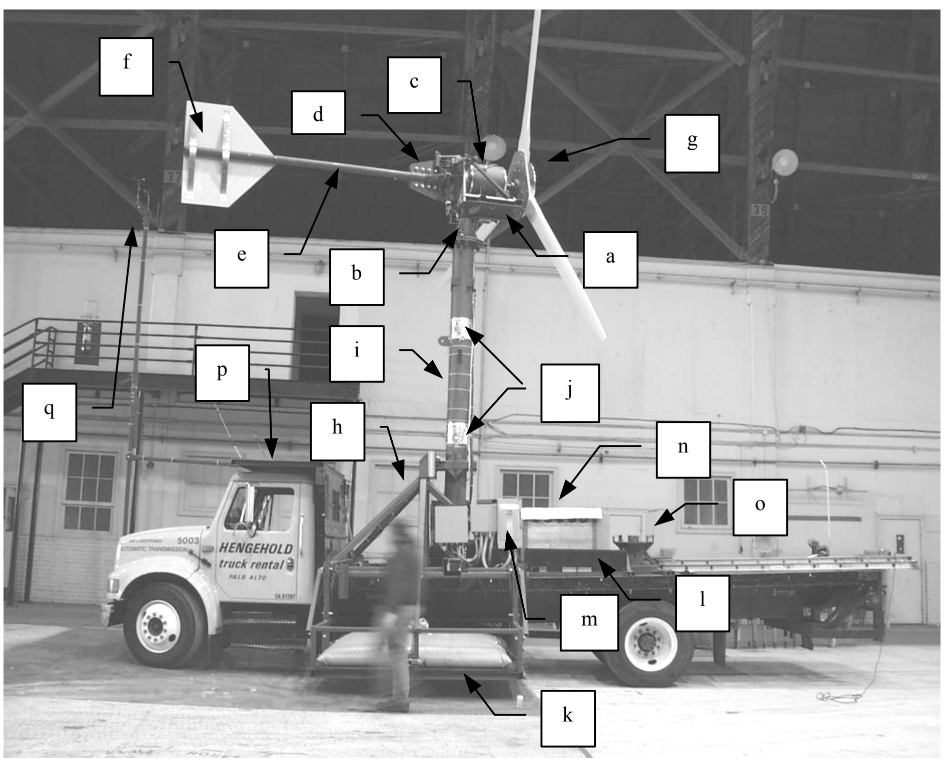


Figure 1. Overspeed control with horizontal furling (top view). Note the offset of the rotor shaft from the yaw axis.



a) variable geometry test fixture
b) yaw assembly
c) generator
d) tail pivot assembly
e) tail boom
f) tail fin
g) rotor system
h) tower system frame
i) tower mast
j) strain gage positions
k) water ballast system
l) battery box
m) disconnect switch
n) 10-kW load bank
o) generator transport frame
p) scatter shield
q) anemometer mast

Figure 2. Side view of test setup in NASA Ames Hangar 2 (note turbine is pointing downwind)

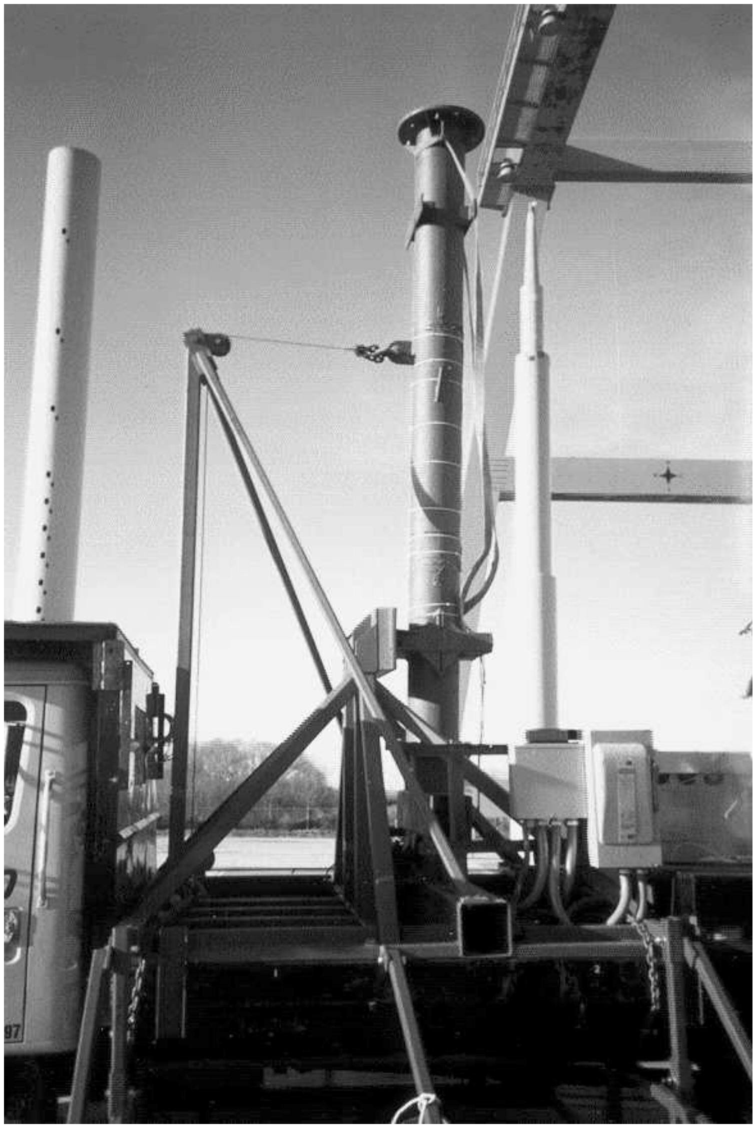


Figure 3. Tower system with gin-pole erection system installed

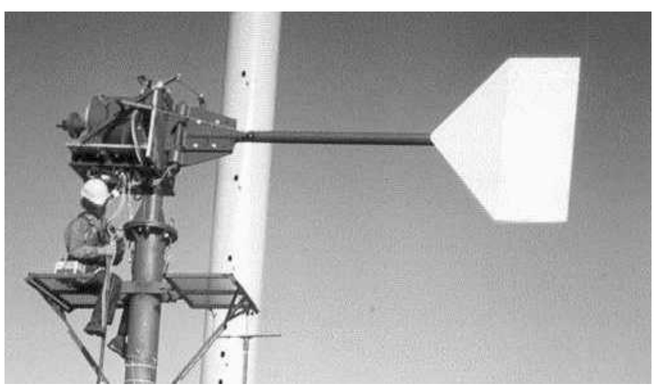


Figure 4. Variable-geometry test-bed mounted to tower without rotor installed. Brian Acker is wiring the generator while aloft on the removable work platform.

Figure 5. View of rotor outside Hangar 2 door. The rotor is mounted to the generator shaft with aluminum compression plates. The turbine is completely furled in this view with the tail angle at 90º. Bill Sorich and Jim Sencenbaugh are installing a weight pan that can be seen above Jim's head (right). Weights were added to move the center of gravity of the turbine aft.

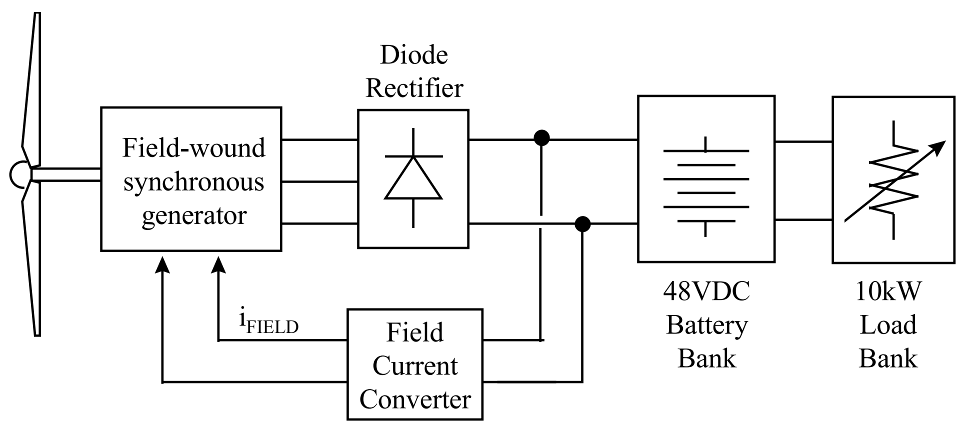


Figure 6. Electrical schematic

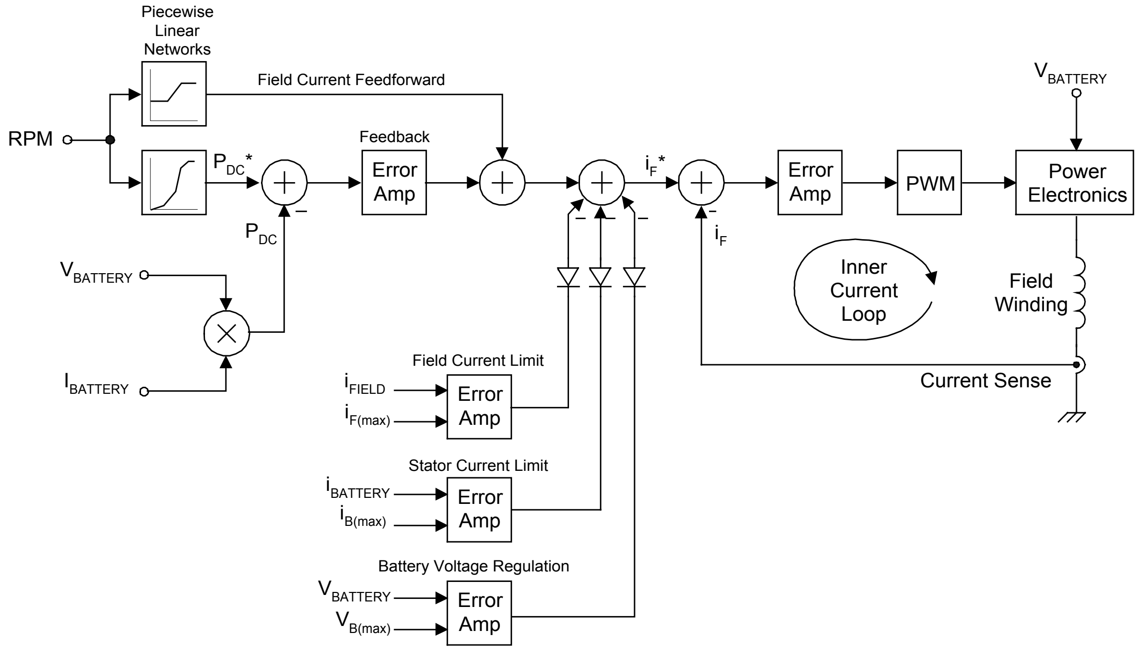


Figure 7. Block diagram of generator control architecture

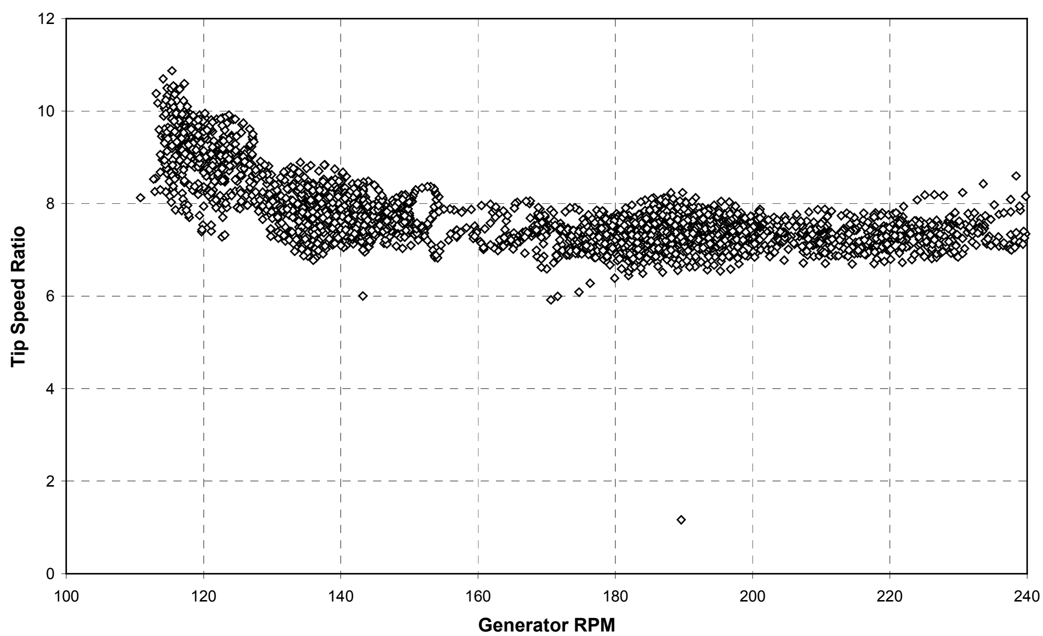


Figure 8. Control of TSR over several test runs

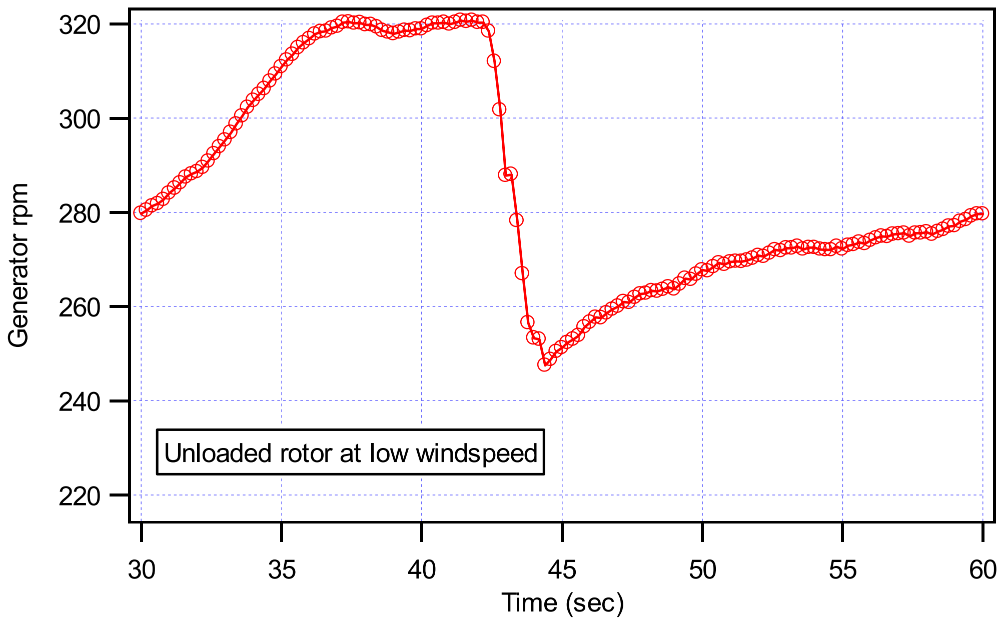


Figure 9. Rotor speed attaining 320 rpm followed by an abrupt reduction due to a stall-flutter condition

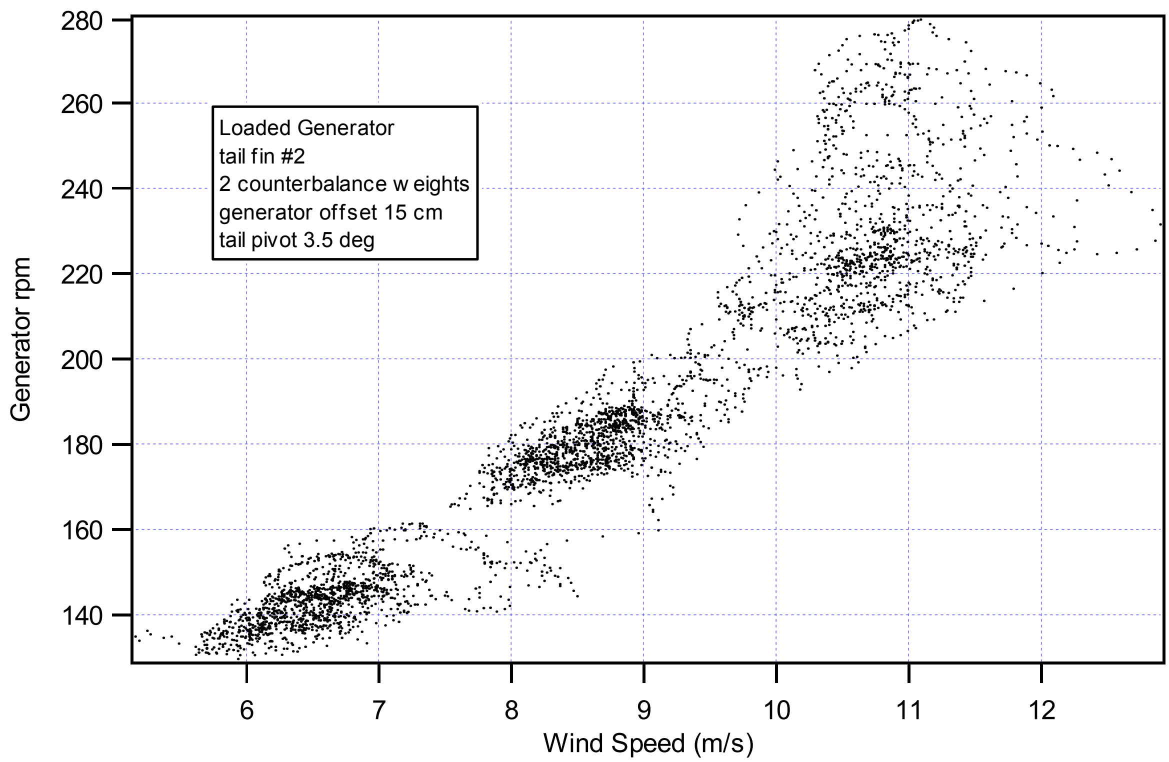


Figure 10. Unsteadiness in wind speed and generator rpm during test runs

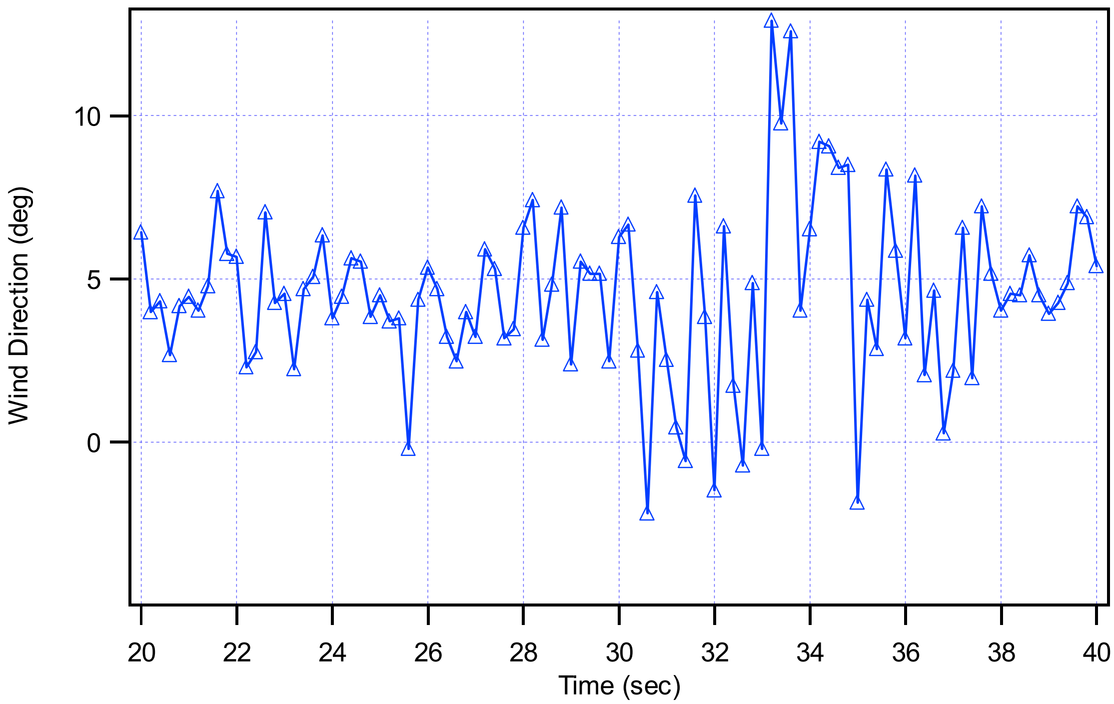


Figure 11. Unsteadiness in wind direction measurement. This behavior was also observed visually.

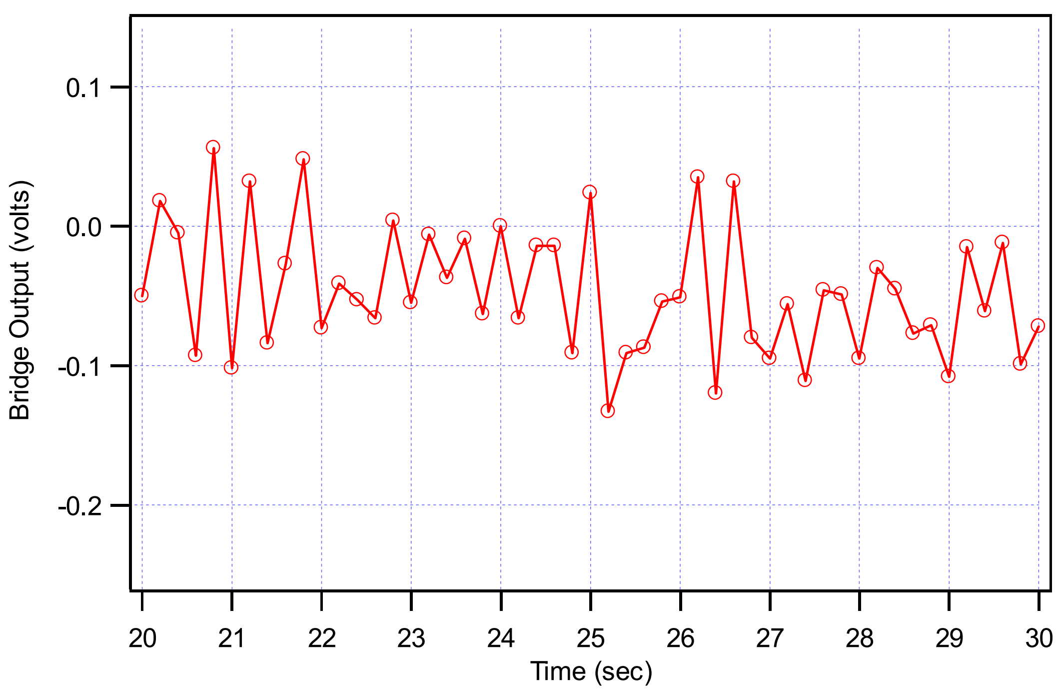


Figure 12. Example tower-bending bridge time series

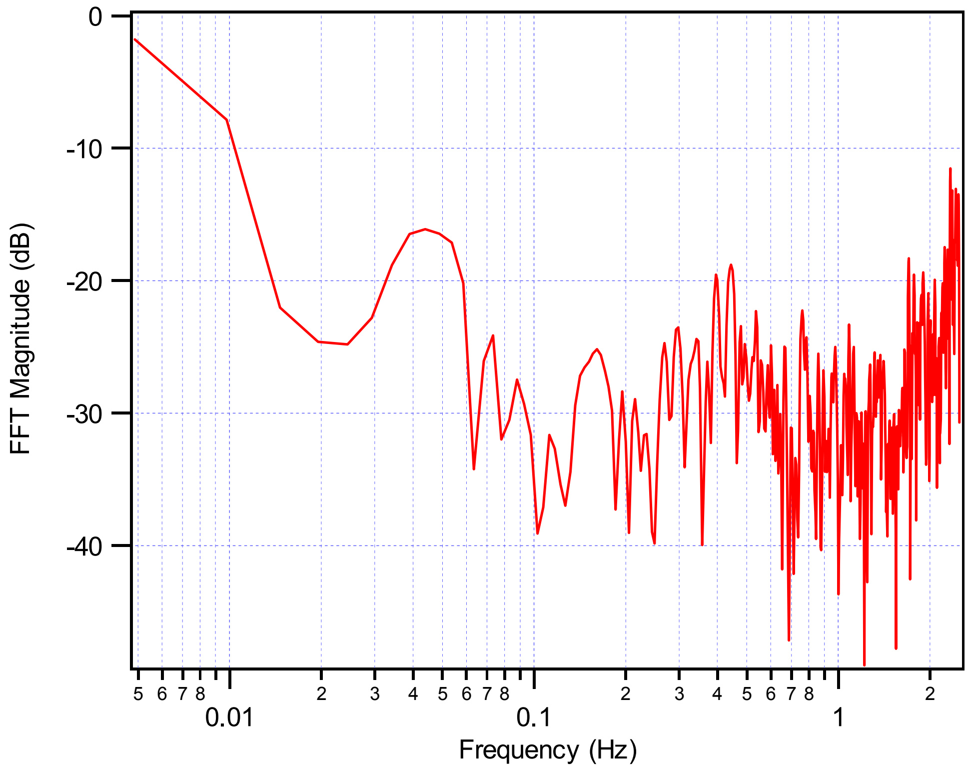


Figure 13. Fast Fourier Transform (FFT) of tower-bending signal indicating aliasing with significant magnitude at one-half the 5 Hz sampling rate